N72-31617

NASA TECHNICAL NOTE

NASA TN D-6901

NASA TN D-6901

ATMOSPHERIC ELECTRICITY CRITERIA GUIDELINES FOR USE IN AEROSPACE VEHICLE DEVELOPMENT

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • SEPTEMBER 1972

1. Report No. NASA TN D-6901	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Atmospheric Electricity Criteria Guidelines for Use in Aerospace Vehicle Development		5. Report Date September 1972 6. Performing Organization Code
7. Author(s) Glenn E. Daniels		8. Performing Organization Report No. M194
9. Performing Organization Name and Address George C. Marshall Space Flight Center Marshall Space Flight Center, Alabama 35812		10. Work Unit No. 976-30-40-00-62 11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D. C. 20546		13. Type of Report and Period Covered Technical Note 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

Lightning has always been of concern for aerospace vehicle ground activities. The unexpected triggering of lightning discharges by the Apollo 12 space vehicle shortly after launch and the more recent repeated lightning strikes to the launch umbilical tower while the Apollo 15 space vehicle was being readied for launch have renewed interest in studies of atmospheric electricity as it relates to space vehicle missions. This report reflects some of the results of these studies with regard to updating the current criteria guidelines.

17. Key Words (Suggested by Author(s))	18. Distribution Statement

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	22	$3.00

* For sale by the National Technical Information Service, Springfield, Virginia 22151

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INTRODUCTION

Atmospheric electricity must be considered in the design, transportation, and operation of aerospace vehicles. The effect of the atmosphere as an insulator and conductor of high-voltage electricity, at various atmospheric pressures, must also be considered. Aerospace vehicles that are not adequately protected can be damaged by the following:

1. A direct lightning stroke to the vehicle or the launch support equipment while on the ground or after launch.

2. Current induced in the vehicle from the transport of a charge from nearby lightning.

3. A large buildup of the atmospheric potential gradient near the ground as a result of charged clouds nearby.

Also, high-voltage systems aboard the vehicle which are not properly designed can arc or break down at low-atmospheric pressures.

The vehicle can be protected as follows:

1. By insuring that all metallic sections are connected by electrical bonding so that the current flow from a lightning stroke is conducted over the skin without any gaps where sparking would occur or current would be carried inside. Reference 1 gives the requirements for electrical bonding.

2. By protecting buildings and other structures on the ground with a system of lightning rods and wires over the outside to carry the lightning stroke into the ground.

3. By providing a zone of protection (as shown in Reference 2 for the lightning protection plan for Saturn Launch Complex 39).

4. By providing protection devices in critical circuits [3].

5. By using systems which have no single failure mode. {The Saturn V launch vehicle uses triple redundant circuitry on the auto-abort system, which requires two out of the three signals to be correct before abort is initiated [4].}

6. By appropriate shielding of units sensitive to electromagnetic radiation.

7. For horizontally flying vehicles, by avoiding potentially hazardous thunderstorm areas by proper flight planning and flight operations. Reference 5 has an excellent discussion on geographic areas where thunderstorms and thus potentially dangerous lightning discharges occur frequently.

If lightning should strike a vehicle or the test stand or launch umbilical tower (LUT), sufficient system checks should be made to insure that all electrical components and subsystems of the vehicle are functional.

THUNDERSTORM ELECTRICITY

On a cloudless day, the potential electrical gradient in the atmosphere near the surface of the earth is relatively low (<300 V/m); but when clouds develop, the potential gradient near the surface of the earth will increase. If the clouds become large enough to have water droplets of sufficient size to produce rain, the atmospheric potential gradient may be sufficient to result in a lightning discharge which would require measured gradients greater than 10 000 volts per meter at the surface. Gradients may be considerably higher at altitude above the surface.

Potential Gradient

The earth-ionospheric system can be considered a large capacitor: the earth's surface as one plate, the ionosphere the other plate, and the atmosphere the dielectric. The earth is negatively charged.

Fair-Weather[1] Potential Gradients

The fair-weather electrical field intensity (the negative of the electrical gradient) measured near the ground is approximately 100 to 300 volts per meter and negative; i.e., the earth is negatively charged and the atmosphere above the earth is positively charged. The fair-weather value of 100 to 300 volts per meter will vary with time at any specific location and will also be different at various locations. These variations in fair weather are caused by the amount of particulate matter in the atmosphere (dust, salt particles, etc.), atmospheric humidity, and location and exposure of the measuring devices [6]. The fair-weather potential gradient decreases with altitude and has a value near zero at 10 kilometers. Fair-weather potential gradient over a 100-meter-high vehicle could result in a 10 000-volt, or greater, potential difference between the air near the ground and the air around the vehicle top, causing the vehicle to assume the charge if not grounded.

Potential Gradients with Clouds

When clouds develop, the potential gradient at the ground increases. Because of the increased potential gradient on days when scattered cumulus clouds occur, severe shock may result from charges carried down metal cables connected to captive balloons. Similarly induced charges on home television antennas have been great enough to explode fine wire coils in antenna circuits in television sets. Damage to equipment connected to wires and antennas can be reduced or prevented by the use of lightning arresters with air gaps close enough to discharge the current before the voltage reaches values high enough to damage the equipment.

Potential Gradients During Thunderstorms

When the cloud develops into the cumulo-nimbus state, lightning discharges result. For a discharge to occur, the potential gradient at a location reaches a value equal to the critical breakdown value of air at that location. Laboratory data indicate this value to be as much as 10^6 volts per meter at standard sea-level atmospheric pressure. Electrical fields measured at the

1. The term fair weather is used to mean without clouds. Also, the term fine weather is sometimes used.

surface of the earth are much less than 10^6 volts per meter during lightning discharges for several reasons:

1. Most clouds have centers of both polarities which tend to neutralize values measured at the surface.

2. Each charge in the atmosphere and its image within the earth resembles an electrical dipole, and the intensity of the electrical field decreases with the cube of the distance to the dipole.

3. The atmospheric electric field measured over land at the surface is limited by discharge currents arising from grounded points, such as grass, trees, and other structures, which ionize the air around the points, thus producing screen space charges.

For these reasons, the measured electrical field at the surface is never more than about 15×10^3 volts per meter. The potential gradient values indicated by measuring equipment at the surface will show high values when the charged cloud is directly overhead. As the horizontal distance between the projection of the charged center of the cloud to the ground and the measuring equipment becomes greater, the readings become lower, reaching zero at some distance, and then change to the opposite sign at greater distances [1, 6].

Corona Discharge

As the atmospheric potential gradient increases, the air surrounding exposed sharp points becomes ionized by corona discharge. The charge induced by a nearby lightning stroke may aid such a discharge. The corona discharge may be quite severe when lightning storms or large cumulus clouds are within about 16 kilometers (10 mi) of the launch pad.

CHARACTERISTICS OF LIGHTNING DISCHARGES

The lightning discharge to the ground, which appears to the eye as a single flash, is usually made up of three or four strokes. These strokes are preceded by a leader stroke of lesser intensity. The characteristics of various types of lightning discharges are summarized in Table 1 [7, 8].

TABLE 1. CHARACTERISTICS OF LIGHTNING DISCHARGES

Type of Lightning	Average Peak Current per Stroke (A)	Maximum Rate of Rise of Current (A/μsec)	Average Amount of Charge Transferred		Average Total Duration of Stroke (msec)	Average Number of Strokes (unitless)	Average Time Between Strokes (msec)	Remarks
			Per Stroke (C)	Total (C)				
Intercloud lightning	100-2000	100-500	1-5	1-5	300	1		
Discrete lightning strokes to ground								
Leader	100		1-5	5	20	1		
Return stroke	20 000	200 000	5	4-20	0.3	3 to 4	40	Peak current exceeding 100 000 A have been measured about 2 percent of the time.
Long continuing current lightning strokes to ground								
Leader	100		1-5	5	20	1		
Return stroke	20 000	10 000	12-40	12-40	200	1		Average current value of 185 A for long periods (175 msec).

Lightning Characteristics for Design

Based on the information in Table 1, the following summary of lightning characteristics should be considered in design:

1. On the launch pad or during ground transportation

a. An average peak current of 20 000 amperes can be expected. The peak current flow is often reached 6 microseconds after start of the stroke, with a fall to one-half the peak value in 24 microseconds. A total flash charge of 5 coulombs is transmitted to the earth with 90 percent of the current flow, after the initiation of the first stroke. Additional strokes will have about the same currents, with the peaks of the currents at 10-millisecond intervals.

b. The maximum peak current will not be greater than 100 000 amperes in 98 percent of the strokes. The peak current flow is reached in 10 microseconds after start of the stroke, and the current then falls to one-half the peak value in 20 microseconds. A total stroke charge of 20 coulombs is transmitted to the earth, with 95 percent of the current flow, after the initiation of the first stroke, at less than 500 amperes.[2]

2. Triggered lightning during flight. The space vehicle while in flight should be capable of withstanding an electrical discharge from triggered lightning. The characteristic of such a discharge is expected to be an average peak current of about 20 000 amperes. The peak current flow is reached in 6 microseconds after the start of the stroke, with a fall to one-half the peak value in 24 microseconds. After the current drops to 185 amperes, it will remain near that level for at least 175 milliseconds (175 000 μsec) before decreasing to zero. There will be only one stroke in the discharge called a long-continuing-current discharge [1,4,7,8,9].

Surges from a Lightning Discharge

If an electrical line, antenna, or other metallic object is struck by a lightning discharge, there will be a surge of current through the object. If the object is grounded and is of sufficient size, then characteristic currents equal to the current in the lightning discharge will be conducted through the object to ground. If the object is not grounded, then the current flow will be less in relation to the resistance of the object and the ground. Metallic objects whose cross sections are too small to carry the current from a lightning stroke may be melted or vaporized.

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2. Recent measurements of currents in Florida lightning strokes by Martin A. Uman (Contract NAS 8-28168) have given a maximum value of rate-of-change of current from zero to peak of nearly 100 000 amperes in 0.5 microsecond (200 000 amperes per microsecond).

Current Flow from a Lightning Discharge

When lightning strikes an object, the current will flow through a path to the true earth ground. The voltage drop along this path may be great enough over short distances to be dangerous to personnel and equipment [2]. Cattle and humans have been electrocuted from the current flow through the ground and the voltage potential between their feet while standing under a tree struck by lightning.

The flow of current in objects struck by lightning will divide into each possible path of resistance, with the lowest resistance paths carrying the greater current inversely proportional to the resistance. Figure 1 illustrates this principle for the Saturn V vehicle on the launch pad.

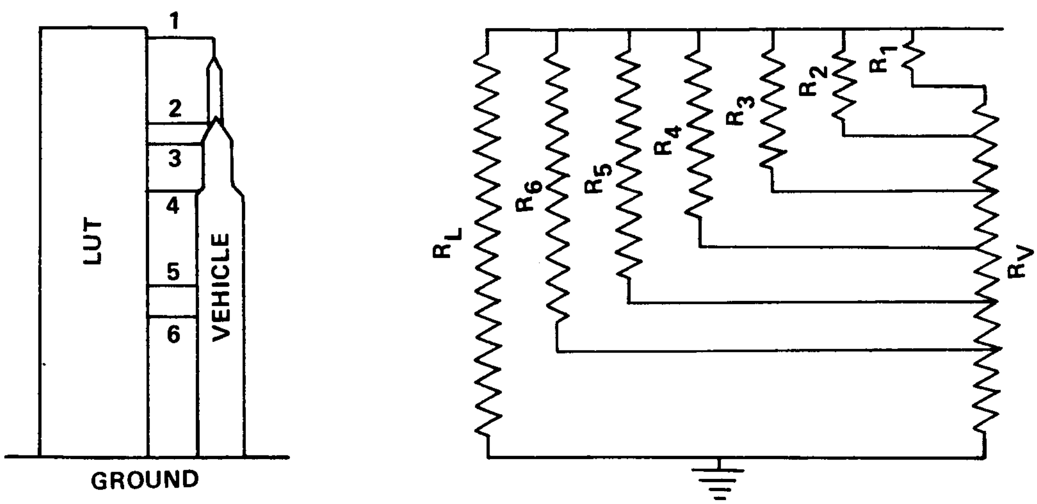

Figure 1. Example of current flow in aerospace vehicle on launch pad and comparable resistance analogy.

Therefore,

$$I_L = \frac{R_L}{R_T} I_T ,$$

where

I_L = current through LUT,

I_T = total current of lightning stroke,

R_L = resistance of LUT,

R_T = total resistance of system,

R_1, R_2, etc. = resistance of each connecting arm to vehicle,

R_V = resistance of vehicle.

In the case of the Saturn V vehicle, a sizable percentage ~30 percent flows through the Saturn V vehicle.

Since lightning usually strikes the highest exposed point, the only way to be certain that damaging currents will not flow through a space vehicle on the launch pad is to either: (1) prevent the lightning discharge to the launch complex or, (2) to conduct the lightning discharge around the launch complex using sufficient mass to carry the current through conductors well insulated (high-resistance supports) from the launch complex equipment.

Radio Interference

When an electrical charge produces a spark between two points, electromagnetic radiation is emitted. This discharge is not limited to a narrow band of frequencies but covers most of the electromagnetic radiation spectrum with various intensities. Most static heard in radio reception is related to electrical discharges, with lightning strokes contributing much of the interference. This interference from lightning strokes is propagated through the atmosphere in accordance with laws valid for ordinary radio transmission and may travel great distances. With the transmission of interference from lightning strokes over great distances, certain frequencies remain prominent, with those near 30 kilohertz being the major frequencies. Interference with telemetering and guidance needs to be considered only when thunderstorms are occurring within 100 kilometers (60 mi) of the space vehicle launch site.

FREQUENCY OF OCCURRENCE OF THUNDERSTORMS

According to standard United States weather observing and recording practice, a thunderstorm is reported whenever thunder is heard at the station.

It is recorded along with other atmospheric phenomena on the standard weather observer's form, indicating when the thunder is heard. The report ends 15 minutes after thunder is last heard. This type of reporting of thunderstorms may contain a report as one, of one or more thunderstorms during a period. For this reason, these types of observations will be referred to as thunderstorm events, i.e., a period during which one or more thunderstorms are reported. Because of the method of reporting thunderstorms, most analyses of thunderstorm data are based on the number of days per year in which thunder is heard one or more times on a day, i.e., thunderstorm days. Reference 10 is a detailed study on frequencies of thunderstorms occurring in the Cape Kennedy area.

Thunderstorm Days per Year (Isoceraunic[3] Level)

The frequency of occurrence of thunderstorm days is an approximate guide to the probability of lightning strokes to earth in a given area. The number of thunderstorm days per year is called the isoceraunic level. A direct lightning stroke is possible at all locations of interest, but the frequency of such an occurrence varies among the locations (Table 2) [2], [3], and [11].

Thunderstorm Occurrence per Day

In a study made using the weather observers data, which reports a thunderstorm when thunder is heard [10], the frequencies were computed on the number of days which had 0, 1, 2, ..., thunderstorms reported, i.e., none or more thunderstorm events. Tables 3 and 4 [11] give this information.

Thunderstorm Hits

There were sufficient data for the summer months (June-August) at Cape Kennedy to make an analysis of the frequency of occurrence of thunderstorm hits as:

3. This word is also spelled isokeraunic.

TABLE 2. FREQUENCY OF OCCURRENCE OF THUNDERSTORM DAYS (ISOCERAUNIC LEVEL)

Location	Mean Number of Days Per Year of Thunderstorms	Monthly Distribution (Percent of Annual Number Days)											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Huntsville	70	1 0.70	3 2.10	6 4.20	8 5.60	11 7.70	19 13.30	22 15.40	18 12.60	9 6.30	1 0.70	1 0.70	1 0.70
River Transportation and New Orleans	75	3 2.25	3 2.25	5 3.75	5 3.75	8 6.0	16 12.0	21 15.75	20 15.0	10 7.5	3 2.25	3 2.25	3 2.25
Gulf Transportation	90	1 0.90	1 0.90	4 3.60	2 1.80	9 8.10	18 16.20	24 21.60	23 20.70	12 10.80	4 3.60	1 0.90	1 0.90
Eastern Test Range	70.09	0.77 0.54	1.94 1.36	4.28 3.00	4.02 2.82	9.73 6.82	18.55 13.00	21.27 14.91	20.23 14.18	13.22 9.27	3.89 2.73	1.18 0.82	0.92 0.64
Panama Canal Transportation	100	1 1.0	1 1.0	4 4.0	2 2.0	9 9.0	18 18.0	24 24.0	23 23.0	12 12.0	4 4.0	1 1.0	1 1.0
West Coast Transportation	6	9 0.54	11 0.66	19 1.14	13 0.78	7 0.42	4 0.24	3 0.18	7 0.42	8 0.48	8 0.48	3 0.24	8 0.48
Vandenberg AFB California	2	5 0.1	15 0.3	15 0.3	5 0.1	2 0.04	1.5 0.03	10 0.2	10 0.2	25 0.5	1.5 0.03	5 0.1	5 0.1
Sacramento	4	6 0.24	16 0.64	12 0.48	15 0.60	9 0.54	6 0.24	3 0.12	3 0.12	10 0.40	12 0.48	5 0.20	3 0.12
Wallops Test Range[a]	40.6	0.5 0.2	1.2 0.5	5.2 2.1	8.4 3.4	12.6 5.1	17.2 7.0	21.7 8.8	20.4 8.3	7.9 3.2	3.2 1.3	1.0 0.4	0.7 0.3
White Sands Missile Range[b]	38.1	0.8 0.3	0.1 0.05	1.8 0.7	4.7 1.8	7.6 2.9	15.2 5.8	30.5 11.6	23.9 9.1	8.7 3.3	5.2 2.0	0.5 0.2	1.0 0.4
Edwards AFB California	4.3	2.3 0.1	2.3 0.1	2.3 0.1	7.0 0.3	4.7 0.2	2.3 0.1	23.3 1.0	25.6 1.1	20.9 0.9	7.0 0.3	2.3 0.1	0 0

a. Data from Norfolk, Virginia

b. Data from Holloman AFB, New Mexico

TABLE 3. FREQUENCIES OF THE OBSERVED NUMBER OF DAYS THAT EXPERIENCED x THUNDERSTORM EVENTS AT CAPE KENNEDY FOR THE 11-YEAR PERIOD OF RECORD JANUARY 1957 THROUGH DECEMBER 1967

x	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Spring	Summer	Fall
0	335	295	308	299	266	187	177	185	228	311	321	334	873	549	860
1	4	9	20	18	43	77	80	89	54	17	6	3	81	246	77
2	2	4	9	10	25	40	47	30	33	9	3	2	44	117	45
3		2	3	3	3	17	26	24	12	4		2	9	67	16
4			1		3	6	9	10	3				4	25	3
5					0	2	2	3					0	7	
6					1	1							1	1	
n	341	310	341	330	341	330	341	341	330	341	330	341	1012	1012	1001

TABLE 4. RELATIVE FREQUENCY OF DAYS THAT EXPERIENCED AT LEAST ONE THUNDERSTORM EVENT AT CAPE KENNEDY

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Spring	Summer	Fall
0.018	0.048	0.097	0.094	0.220	0.433	0.481	0.457	0.309	0.088	0.027	0.021	0.137	0.458	0.141

1. A thunderstorm actually reported overhead.

2. A thunderstorm first reported in a sector and last reported in the opposite sector, if it is assumed that thunderstorms move in straight lines over small areas. This information is listed in Tables 5 and 6 [3].

Hourly Distribution of Thunderstorms

Figure 2 presents the empirical probability that a thunderstorm will occur in the Cape Kennedy area at each hour of the day during each month. The highest frequency of thunderstorms (24 percent) is around 1600 EST in July. A thunderstorm is reported by standard observational practice if thunder is heard, which it can be over a radius of approximately 25 kilometers. Thus, the statistics presented in Figure 2 are not necessarily the probability that a thunderstorm will "hit," for example, a vehicle on the launch pad, or occur at a given location on Cape Kennedy.

TABLE 5. FREQUENCIES OF THE OBSERVED NUMBER OF DAYS THAT EXPERIENCED x THUNDERSTORM HITS AT CAPE KENNEDY FOR THE 11-YEAR PERIOD OF RECORD JANUARY 1957 THROUGH DECEMBER 1967

x	Jun	Jul	Aug	Summer
0	293	305	300	898
1	27	24	30	81
2	5	6	7	18
3	3	3	2	8
4 or more	2	3	2	7
Total	330	341	341	1012

TABLE 6. RELATIVE FREQUENCY OF DAYS THAT EXPERIENCED AT LEAST ONE THUNDERSTORM HIT AT CAPE KENNEDY

Jun	Jul	Aug	Summer
0.112	0.106	0.121	0.113

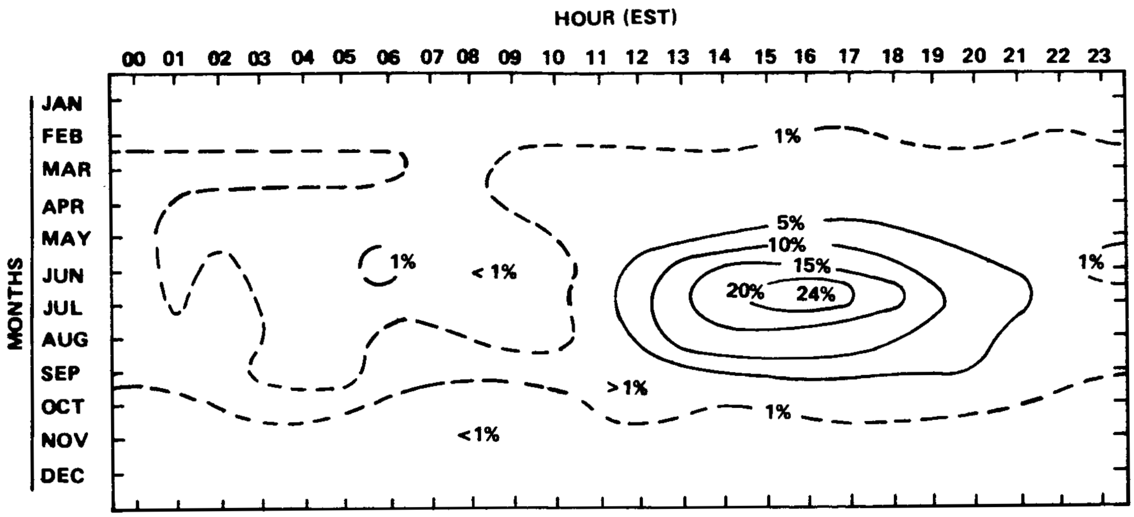

Figure 2. Probability (%) of occurrence of thunderstorms by months versus time of day in the Cape Kennedy area.

FREQUENCY OF LIGHTNING STROKES TO EARTH

Only limited data have been obtained on the number of lightning strokes to ground. These data are difficult to obtain because lightning stroke measuring equipment does not usually differentiate between cloud-to-ground and cloud-to-cloud strokes. In addition, the equipment may record a strong stroke at a great distance and not record a weak stroke much closer. Therefore, the most reliable data of cloud-to-ground lightning strokes have been obtained visually. Such observations are limited in both number and length of time of observations.

Comparison of data published on cloud-to-ground lightning strokes from measuring equipment, visual observations, actual strikes to objects from insurance claims and magnetic links, and electrical outages confirms that the average number of lightning strokes per year to objects of different heights given in Table 7 is realistic of the Cape Kennedy area [12-14].

Table 7 should not be interpreted to mean that 4.4 lightning strokes will be observed on a 152-meter (500-ft) object at Cape Kennedy each year. There may be no strokes or very few during a year, then in another year, a considerable number of strokes. Also one can assume that all strokes that occur will not be observed or known to have occurred within the launch area.

TABLE 7. ESTIMATE OF THE AVERAGE NUMBER OF LIGHTNING STROKES PER YEAR FOR VARIOUS HEIGHTS FOR CAPE KENNEDY

Height (m)	Height (ft)	Average Number of Lightning Strokes per Year
30.5	100	0.4
61.0	200	1.1
91.4	300	2.3
121.9	400	3.5
152.4	500	4.4
182.9	600	5.3
213.4	700	5.8

Although numerous aerospace vehicles have been launched from Cape Kennedy during the last 10 years, only a few lightning strokes are known to have struck the launch complexes until Apollo 15, when 11 separate strokes were known to have struck the launch complex during 5 different days between June 14 and July 21, 1971 (a period of 37 days) [15].

Work is underway to develop a statistical model of probability of lightning strokes to the ground for each month at Cape Kennedy.

STATIC ELECTRICITY

A static electrical charge may accumulate on an object from its motion through an atmosphere containing raindrops, ice particles, or dust. A stationary object, if not grounded, can also accumulate a charge from wind-borne particles (often as nuclei too small to be visible) or rain or snow particles striking the object. This charge can build up until the local electric field at the point of sharpest curvature exceeds the breakdown field. The quantity of maximum charge will depend on the size and shape of the object (especially if sharp points are on the object). Methods of calculating this charge are given in Reference 7.

If a charge builds up on a vehicle on the launch pad which is not grounded, any discharges which occur could ignite explosive gases or fuels, interfere with

radio communications or telemetry data, or cause severe shocks to persons. Static electrical charges occur more frequently during periods of low humidity and can be expected at all geographical areas.

ELECTRICAL BREAKDOWN OF THE ATMOSPHERE

The atmosphere of the earth at normal sea-level pressure (101 325 N/m^2) is an excellent insulator, having a resistance greater than 10^{16} ohms for a column 1 square centimeter in cross section and 1 meter long. When there is a charge in the atmosphere, ionization takes place, thus increasing the conductivity of the air. This charge can be from either cloud buildups or electrical equipment. If the voltage is increased sufficiently, the ionization will be high enough for a spark to discharge.

The breakdown voltage (voltage required for a spark to jump a gap) for direct current is a function of atmospheric pressure. The breakdown voltage decreases with altitude until a minimum is reached of 327 volts per millimeter at an atmosphere pressure of 760 newtons per square meter (7.6 mb), representing an altitude of 33.3 kilometer. Above and below this altitude, the breakdown voltage increases rapidly [16], being several thousand volts per millimeter at normal atmospheric pressure (Fig. 3).

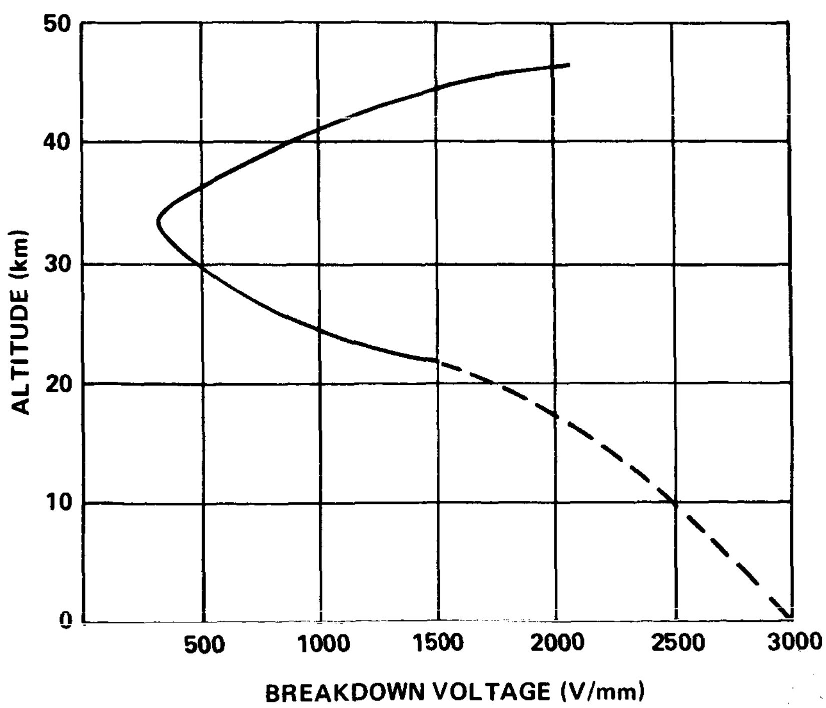

Figure 3. Breakdown voltage versus altitude.

The breakdown voltage is also a function of frequency of an alternating current. With an increase of frequency the breakdown voltage decreases. A more complete discussion can be found in Reference 17.

The following safety measures can be taken to prevent arcing of high voltage in equipment:

1. Have equipment voltages off at the time the space vehicle is going through the critical atmospheric pressures. Any high-voltage capacitors should have bleeding resistors to prevent high-voltage charges remaining in the capacitors.

2. Eliminate all sharp points and allow sufficient space between high-voltage circuits.

3. Seal high-voltage circuits in containers at normal sea-level pressures.

4. Have materials available to protect, with proper use, against high-voltage arcing by potting circuits.

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National Aeronautics and Space Administration
Marshall Space Flight Center, Alabama 35812
April 19, 1972
976-30-40-00-62

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NASA-Langley, 1972 —— 20

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